Winter Lake Drawdown as a Strategy for Zebra Mussel (*Dreissena polymorpha*) Control: Results of Pilot Studies in Minnesota and Pennsylvania

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Abstract

Winter drawdown of impounded lakes has been suggested as a potential zebra mussel (*Dreissena polymorpha*) control strategy that warrants further investigation. We evaluated this control method on two impounded lakes recently invaded by zebra mussels--- Lake Zumbro in southeastern Minnesota and Edinboro Lake in northwestern Pennsylvania. Lake Zumbro is a 245 ha impoundment of the Zumbro River which serves as a reservoir for hydropower generation, recreational boating, and fishing. Edinboro Lake, by contrast, is a 97 ha glacial kettle lake augmented by a 2.5 m high dam on its outlet. Surveys of Lake Zumbro by the Minnesota Department of Natural Resources and Edinboro Lake by the Pennsylvania Department of Environmental Protection subsequent to the discovery of zebra mussels in the fall of 2000 revealed that first-year zebra mussels were fairly evenly distributed upon suitable substrate in the littoral zones of both lakes. After consulting with local scientists, government officials, and resource managers, both states independently decided to initiate 1.5 m winter drawdowns for the purpose of zebra mussel control. Both lake surfaces froze during the winter 2000 drawdown period and 45 cm of snowpack covered Edinboro Lake. Lake Zumbro was held at its target drawdown depth for 10 days while Edinboro Lake was held for 7 days. Qualitative post-drawdown investigations of Lake Zumbro suggested that near total zebra mussel mortality occurred in the dewatered zone of the lake but mussels successfully overwintered in waters deeper than the maximum drawdown depth. A quantitative post-drawdown survey of Edinboro Lake, however, revealed that the majority of mussels in water deeper than 0.75 m survived the drawdown, possibly as a result of the mitigating effects of the heavy snow cover on the lake. Mean littoral-sublittoral zebra mussel density in Edinboro Lake decreased 78% following the drawdown and peak density shifted from 290 m-2 at 0.75 m depth before the drawdown to 76 m-2 at 1.4 m depth after the drawdown. A second 1.5 m drawdown was conducted on Edinboro Lake in the fall of 2001. This time the target depth was held for 10 days. The weather was considerably milder during the second drawdown trial, and neither ice nor snow covered the lake. Despite these milder conditions, the second drawdown of Edinboro Lake resulted in significantly more zebra mussel control. Mean zebra mussel density declined by 99% and peak zebra mussel density decreased from 745 m-2 to 10 m-2. We conclude that fall/winter lake drawdowns can be an effective management strategy on some zebra mussel infested lakes with suitable water level control structures. Total elimination of the organism with this management technique is unlikely, however, and resource managers are advised to carefully consider potential costs and benefits before attempting fall/winter lake drawdowns for zebra mussel control.

Keywords: aerial exposure, drawdown, *Dreissena polymorpha*, freeze, freezing, lake, mortality, zebra mussel

INTRODUCTION

Laboratory research has shown that freezing air temperatures are highly lethal to zebra mussels (*Dreissena polymorpha*) within a matter of hours. Paukstis et al. (1996) documented an 88 percent mortality rate for zebra mussels gradually acclimated to a temperature of 2.0 °C and then aerially exposed to freezing temperatures for 2.25 h. Payne (1992) reports that the time required for 100 percent mortality (LT_{100}) of aerially exposed zebra mussels ranges from 0.5 h at -10.0 °C to greater than 48 h at 0.0 °C for individual (non-clustered) mussels under laboratory conditions. Clustered/aggregated mussels had better survivorship than non-clustered mussels, with LT_{100} times ranging from slightly less than 2 h at -10.0 °C to over 48 h at both -1.5 °C and 0.0 °C. Accordingly, winter lake drawdowns to expose zebra mussels to freezing ambient air temperatures have been proposed as a potential control strategy that warrants further investigation (Payne, 1992; Clarke et al., 1993; Heath, 1993; Paukstis et al., 1999). While limited field demonstrations have been conducted to show the potential efficacy of this technique (e.g., Miller et al., 1994), no documented attempts have been made to utilize and evaluate winter lake drawdowns for zebra mussel control on whole-lake systems.

For these pilot studies, we independently conducted “winter” lake drawdowns on two North American lakes—Lake Zumbro in southeastern Minnesota and Edinboro Lake in northwestern Pennsylvania (Figure 1, Table 1). Lake Zumbro is a 245 ha impoundment of the Zumbro River which serves as a reservoir for hydropower generation, recreational boating, and fishing. A typical riverine impoundment, Lake Zumbro is approximately 8.3 km long with an average width of 400 m. The upstream third of the lake is relatively shallow (3-4.5 m) and heavily silted with little hard substrate. The downstream portion of the lake is deeper with a maximum depth of 13.1 m near the dam. Shorelines are steep, and littoral substrate varies from sand and scattered rocks to riprap for shoreline stabilization to limestone bedrock. Sediments in the main lake channel are soft and unconsolidated. Conversely, Edinboro Lake is a 97 ha glacial kettle lake augmented by a 2.5 m concrete dam to power a grist mill in the early 1900s. The littoral substrate is composed of old tree stumps, aquatic macrophytes, gravel, cobble, and boulders added for shoreline stabilization. At depths greater than 2.4 m (roughly half of the areal extent of the lake), lake sediment is dominated by organic muck.

Table 1. Characteristics of study lakes.

	Lake Zumbro	Edinboro Lake
Geographic location	Southeastern MN, USA	Northwestern PA, USA
Latitude	44° 12’ 43” N	41° 52' 59" N
Longitude	92° 28’ 44” W	80° 08' 13" W
Lake Type	Reservoir	Glacial kettle
Surface area (ha)	245	97
Littoral area (ha)	106	14
Mean depth (m)	4.5	3
Z_{max} (m)	13.1	10
Maximum fetch (km)	8.3	1.85
Trophic Status	Eutrophic	Eutrophic
Zebra mussels first discovered	Fall 2000	Fall 2000

One commonality between these lakes is that zebra mussels (*Dreissena polymorpha*) were discovered for the first time in their waters in the fall of 2000. Preliminary inspections indicated that zebra mussels were scattered throughout the shoreline area of both lakes at approximate densities of zero to twelve mussels per 25-30 cm diameter rock. After extensive discussions with local stakeholders, scientists, and resource managers, both states decided to attempt winter lake drawdowns in an effort to control or eradicate the newly discovered invaders.

METHODS

We conducted these drawdown trials independently without prior collaboration. Not surprisingly, then, research methodology varies between the authors. Nonetheless, many similarities exist and these separate pilot studies allow for important comparisons and contrasts. Because of significant methodological differences, however, both lake drawdowns are treated separately here.

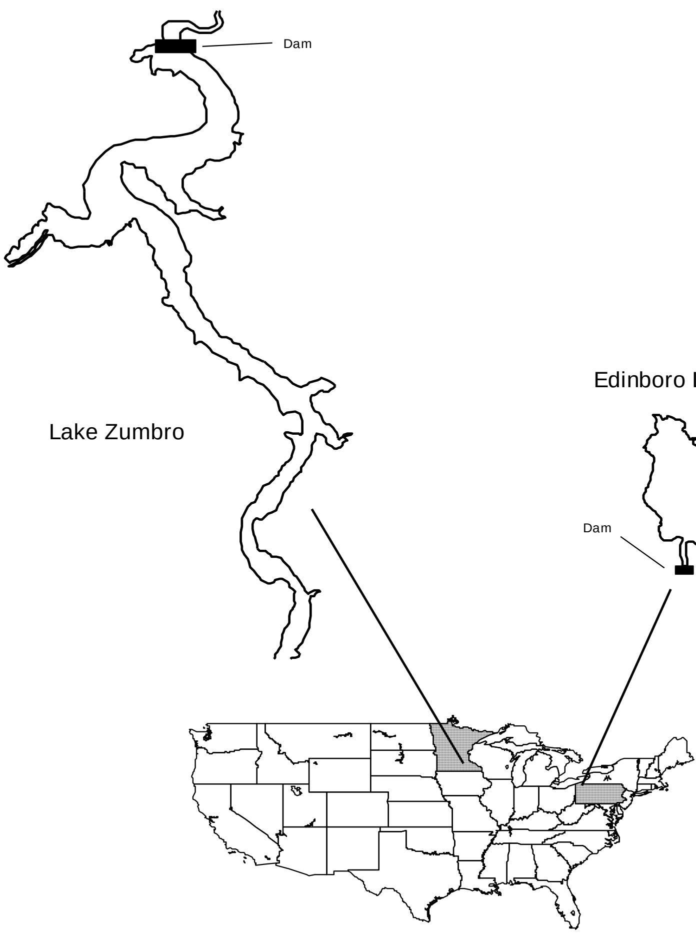

Figure 1. Site map of the study area.

Lake Zumbro, MN

The Lake Zumbro mitigation drawdown was initiated on 20 November 2000. The target drawdown depth was set at 1.5 m even though it was suspected that zebra mussels were present in deeper waters and additional drawdown capability was present. This target depth was selected based on input from stakeholders in order to minimize impact to non-target species and hydropower generation capabilities. Although aerial exposure to freezing temperatures causes complete zebra mussel mortality within a matter of hours under laboratory conditions, exposure times to achieve adequate kill under natural (i.e., variable) conditions may be considerably longer (Paukstis et al., 1999; Tucker et al., 1997). For example, mussel survivorship to aerial exposure can be greatly enhanced in localized microhabitats with high relative humidity (Paukstis et al., 1999; Ricciardi et al., 1995). Therefore, 10 d was selected as the target drawdown duration. The target drawdown depth was reached on or about 6 December 2000 and held for 10 d. Lake refill began on 15 December 2000 but was terminated when the lake reached 0.75 m below full pond because of ice safety concerns. Lake Zumbro was then held at 0.75 m below full pond for the remainder of the winter.

Lake Zumbro was qualitatively surveyed pre-, during, and post-drawdown. Shoreline substrate was inspected via wading at stations 0, 0.8, 4.0, 6.4, and 8.0 km above the dam (Figure 2) in October 2000. These same sites were revisited in February 2001. Relative zebra mussel abundances were visually estimated on rocks and other hard substrate. Mussels were determined to be dead based on lack of response of gaped individuals to insertion of a probe. Multi-plate artificial substrate samplers with detachable microscope slides were deployed the following spring to sample post-drawdown zebra mussel recruitment. Plankton tows were also collected the following summer to estimate veliger densities and qualitative diving surveys were conducted to estimate drawdown efficacy.

Edinboro Lake, PA

Quantitative sampling of the Edinboro Lake zebra mussel population was conducted on 8-9 November 2000. The goals of this sampling were 1) to better understand the distribution of zebra mussels throughout the lake in order to evaluate the likelihood that a mitigation drawdown would be successful and 2) to obtain a quantitative estimate of the Edinboro Lake zebra mussel population. A stratified random sampling design was employed, where water depth was the stratified variable. A buoy was placed in the center of the lake at Z_{max} (approximately 10 m). Nine transects were established radiating from the center of the lake to shoreline points based on randomly generated compass bearings. These transects were sampled at regular depth intervals (either 0, 0.75, 1.5, 3.0 and 6.1 m or 0, 0.75, 1.5, 2.4, and 3.0 m depending on transect) for a total of 45 sampling stations (see Figure 3 for an idealized sampling plan). Sampling locations were recorded using a hand-held GPS unit for future reference. Sampling was conducted by using either a Petite Ponar sampler (225 cm^2) on soft substrates or by rock picks along shoreline areas. Exposed rock surface area was estimated by wrapping the portion of the rock above the sediment-water interface in aluminum foil and comparing the weight of the foil with a known standard. Samples were composited by sampling depth in order to reduce measurement error (USEPA, 1998), resulting in one sample for each depth stratum sampled. This sampling event served as the “baseline” survey prior to the initiation of the first Edinboro Lake drawdown.

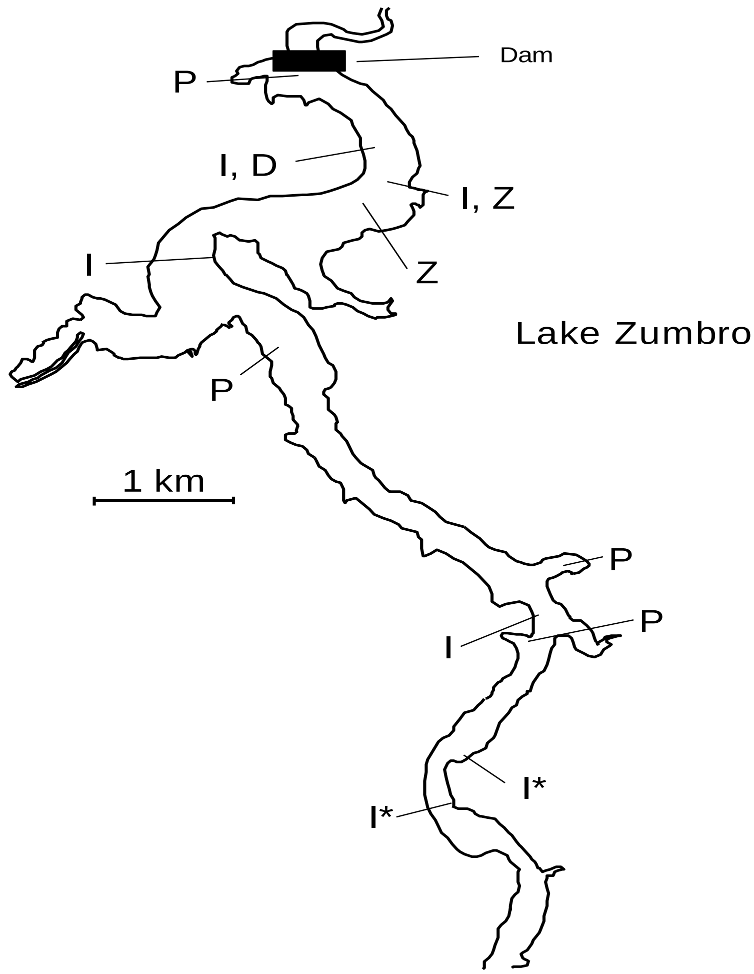

Figure 2. Map of Lake Zumbro showing sampling locations. I=shoreline inspection, D=diving survey, P=multi-plate sampler, Z=zooplankton tow. Sites free of zebra mussels are denoted by an asterisk (*).

Edinboro Lake has undergone two discrete drawdown trials since zebra mussels were first discovered in the fall of 2000. The first drawdown for zebra mussel control was initiated on 9 December 2000. As was the case with Lake Zumbro, the target drawdown depth was set at 1.5 m—the lowest water level the Edinboro Lake outlet dam can reliably produce. In consideration of the limited ecological validity of laboratory LT_{100} values as discussed above, 7 d was selected as the target drawdown duration. The target drawdown depth was reached on or about 16

January 2001 and held for 7 d. Refill began on 23 January 2001 and full pond was established by early February 2001. The same sampling stations established during the baseline survey were re-sampled on 3 May 2001 using the methodology described above.

Because of possible diminished zebra mussel kill resulting from heavy snowpack during the 2000 drawdown, a second drawdown trial commenced the following year on 5 November 2001. The target drawdown depth was again set at 1.5 m. This depth was reached on or about 23 November 2001 and held for 10 d, with refill beginning on 3 December 2001. Quantitative pre- and post-drawdown sampling was conducted on 31 October 2001 and 1 May 2002 using the methodology described above.

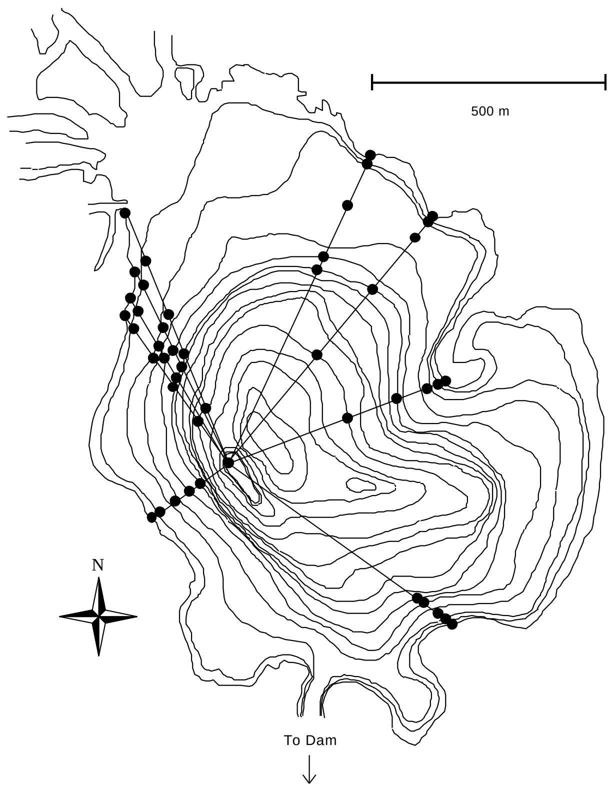

Figure 3. Bathymetric map of Edinboro Lake showing idealized sampling locations. Sampling stations (N=45) are represented by black circles. Each contour line represents a 0.61 m change in depth.

In addition to the quantitative pre- and post-drawdown surveys, dewatered shoreline areas were visually inspected during each drawdown and qualitative SCUBA diving surveys were conducted by others.

RESULTS

Lake Zumbro, MN

Baseline Observations

Zebra mussels were common throughout the wadeable shoreline area of Lake Zumbro in the fall of 2000 (prior to the drawdown). Every second or third rock examined in the downstream two-thirds of the lake had 1-12 zebra mussels attached to its underside. Two distinct size classes appeared to be present: mussels with shell lengths 6-10mm (the dominant class) and mussels with shells in the 13-17mm range. No zebra mussels were found at the most upstream sampling station (8 km above the dam), presumably because of the lack of suitable hard substrate for colonization (Figure 2).

2000 Drawdown Trial

The early winter of 2000 was particularly cold in the northeastern United States. Nighttime temperatures in the -15.0 °C range were common during the drawdown period in the vicinity of Lake Zumbro. Some ice set up along the shoreline during the drawdown, but snowfall was minimal and no snow cover was present.

A mid-drawdown survey was conducted on 28 November 2000 when the water level was approximately 80% of the target depth. Zebra mussel mortality appeared to be near total in dewatered areas based on lack of response of gaped individuals to the insertion of a probe. Even mussels on dewatered substrate beneath the ice cover were dead. One notable exception to the otherwise total zebra mussel mortality occurred near the upstream extent of the Lake Zumbro zebra mussel population. In this area, a few mussels receiving melt water runoff from an adjacent paved area were still alive.

Qualitative diving surveys following the drawdown in July 2001 confirmed that near total zebra mussel mortality occurred in the dewatered zone of Lake Zumbro. Zebra mussels in water deeper than 1.5 m survived, however, and large (38-50 mm) zebra mussels were noted at depths of 3-4 m. Successful zebra mussel spawning and recruitment were also documented the following summer. Mean veliger densities of 4900/m^3 were documented in July 2001 and dense colonization of both dewatered and deeper depths by young-of-year zebra mussels was confirmed by divers in August 2001. In short, a large, reproductively viable population of zebra mussels remained in Lake Zumbro subsequent to the drawdown.

Edinboro Lake, PA

Baseline Observations

The results of the baseline (pre-drawdown) zebra mussel survey conducted in November 2000 revealed that zebra mussels were confined to the shallow littoral and sub-littoral zones of the lake. Zebra mussels reached a peak density of approximately 290/m^2 in 0.75 m of water and then decreased exponentially to 14.81/ m^2 at 1.5 m of depth (Figure 4). No zebra mussels were found in waters exceeding 2.4 m of depth due to substrate and, seasonally, low oxygen limitations.

2000 Drawdown Trial

The winter of 2000 was also marked by extremely cold temperatures in northwestern Pennsylvania. Air temperatures averaged -5.23 °C during the period of the drawdown and sub-freezing temperatures were achieved each day. The Edinboro Lake area also receives “lake-effect” snowfall from Lake Erie, and record season snowfall totals (upwards of 450 cm) were recorded in the general vicinity. The lake surface froze just prior to the commencement of the drawdown and heavy snowpack (approximately 45 cm thick) covered the lake at all times.

The exposed shoreline area of Edinboro Lake was inspected periodically throughout the drawdown. The overwhelming majority of exposed individuals were dead based on lack of response of gaped individuals to prodding. These observations are limited to within roughly the first 0.5 meters of drawdown depth, however, because thick ice and snow cover precluded observation of mussels in deeper waters.

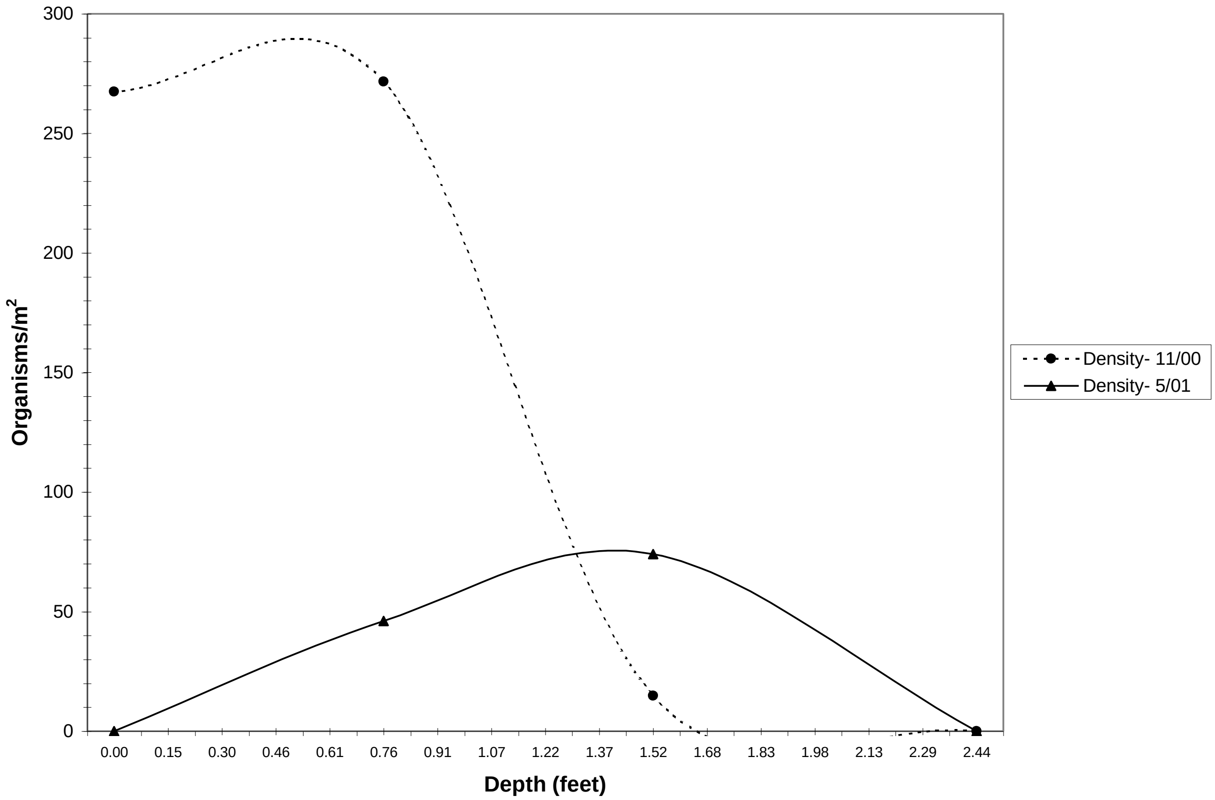

Figure 4. Zebra mussel density v. depth in Edinboro Lake before and after the 2000 drawdown. Each data point represents a single composited sample. Therefore, no error bars are provided.

Quantitative sampling the following spring revealed a shift in peak mussel density from approximately 290/ m^2 at 0.75 m depth in November 2000 (pre-drawdown) to approximately 76/ m^2 at 1.4 m depth in May 2001 (post-drawdown; Figure 4). No live zebra mussels were found immediately along the shoreline ("0 m" depth), and mean littoral-sublittoral densities decreased 78 percent from 184.6 $\pm$ 84.9 to 40.1 $\pm$ 21.6 (Figure 5).

Data from the October 2001 survey indicate that successful zebra recruitment did occur following the 2000 drawdown. Zebra mussels had re-colonized the immediate shoreline area to a density of 208.75/m^2 and peak densities increased by nearly an order of magnitude to over 745/ m^2 at the end of the 2001 growing season. Though mussels were considerably more abundant, the mussel density-depth curve again resembled baseline conditions (Figure 6).

2001 Drawdown Trial

Weather during the fall of 2001 was markedly milder than during the previous drawdown. The mean air temperature during the drawdown period was 7.72 °C with sub-freezing temperatures recorded on only 5 occasions. There was no measurable snowfall during this period and the lake surface did not freeze.

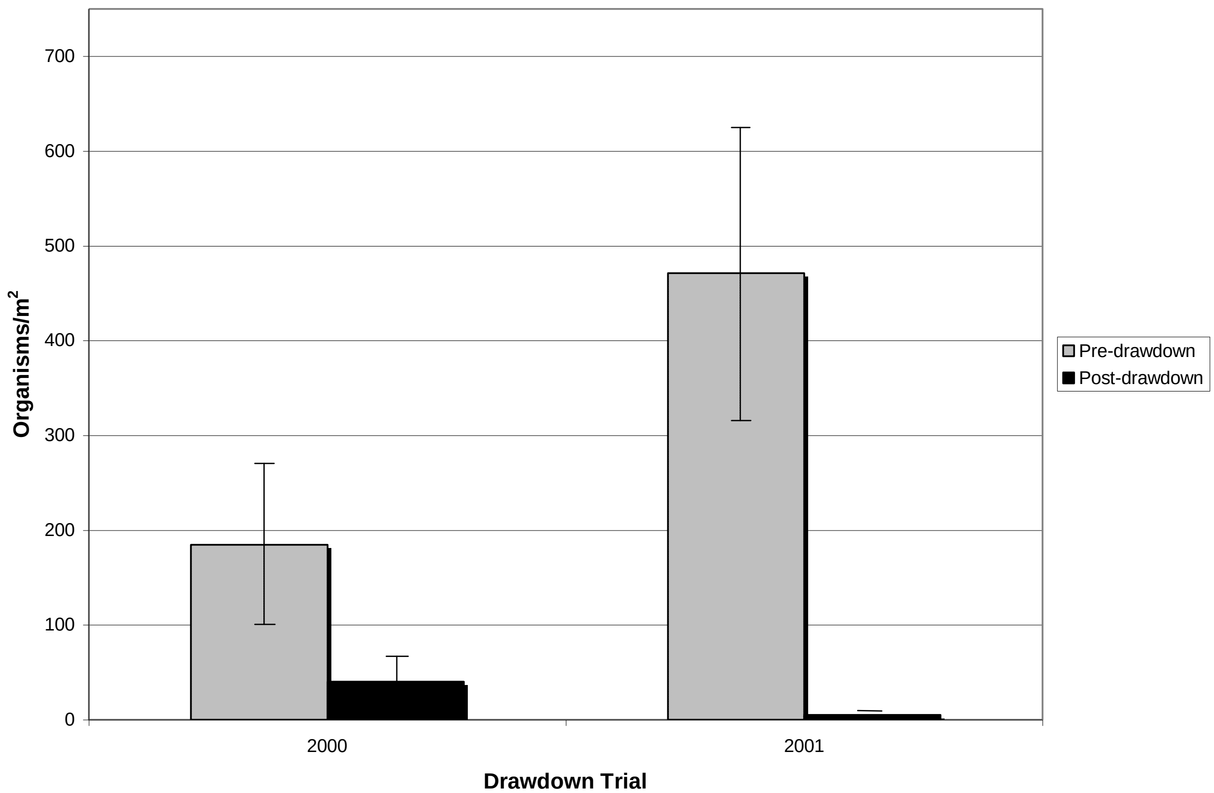

Figure 5. Mean zebra mussel density in the littoral and sublittoral zones of Edinboro Lake before and after each drawdown trial. Error bars are $\pm$ 1 SE.

Despite the unusually mild weather conditions, this latter drawdown trial appears to have been significantly more effective than the former. Mid-drawdown shoreline inspections again revealed widespread and near-total zebra mussel mortality in the dewatered zone of the lake. Because snowpack didn't hinder search efforts as during the previous drawdown, more dewatered lake area was inspected. The presence of large (>20 mm) living zebra mussels in areas that were theoretically dewatered during the 2000 drawdown provided additional evidence that some mussel survival occurred in this zone during the prior drawdown trial.

Post-drawdown sampling revealed dramatic decreases in zebra mussel densities following the 2001 drawdown. Peak mussel density decreased from over 745/m^2 at 0.75 m depth in October 2001 to 10/m^2 at this depth in May 2002. As during the previous drawdown trial, no live zebra mussels were detected along the immediate shoreline area following the 2001 drawdown. Mean littoral-sublittoral zebra mussel densities decreased from 471.2 $\pm$ 155.1 to 4.9 $\pm$ 2.9—a 99% decline (Figure 5). It should be noted, however, that zebra mussels are known to be locally abundant in Edinboro Lake on suitable substrate (e.g., old tree stumps) at depths just beyond the influence of this drawdown. Although these deep substrates were not sampled during the present study, there is no reason to suspect that zebra mussels in these areas suffered any significant overwintering mortality.

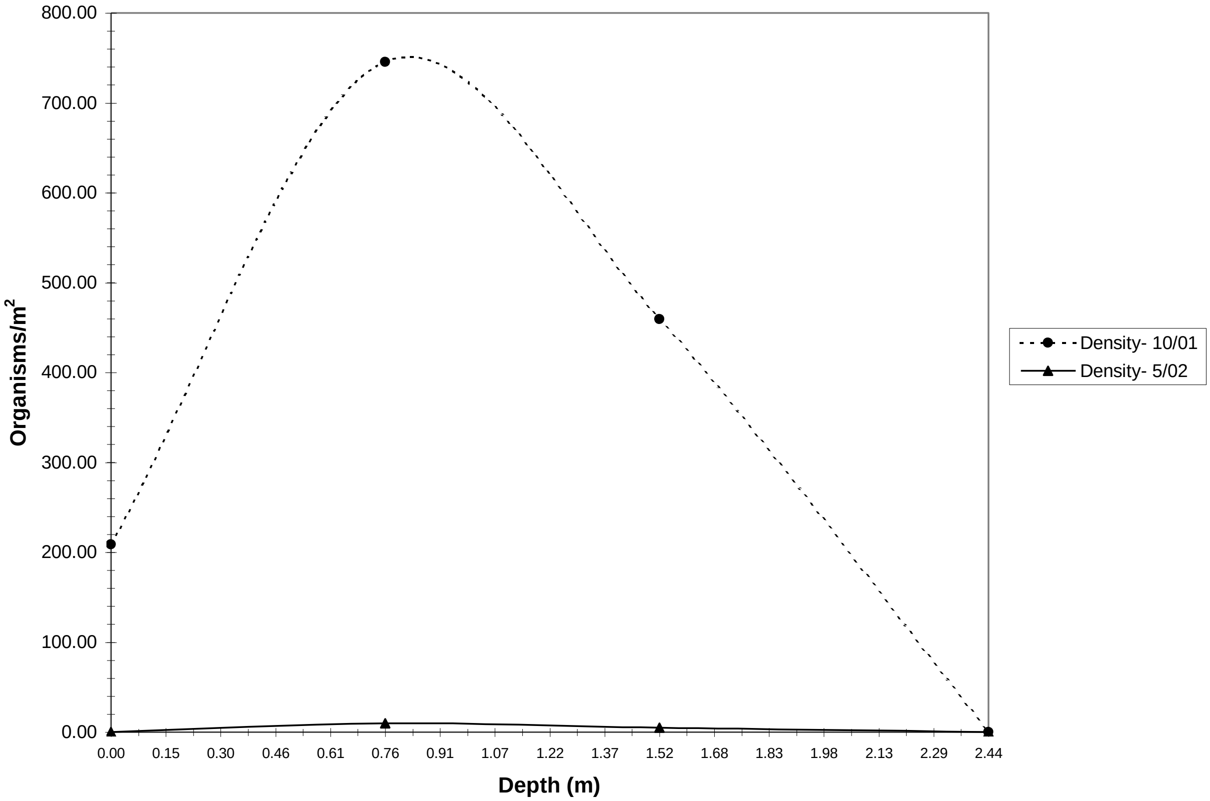

Figure 6. Zebra mussel density v. depth in Edinboro Lake before and after the 2001 drawdown. Each data point represents a single composited sample. Therefore, no error bars are provided.

DISCUSSION

In both the Lake Zumbro and Edinboro Lake drawdowns, there was overwhelming mortality of zebra mussels in the dewatered zones of the lakes. There were instances in both lakes, however, where occasional live zebra mussels were observed in the dewatered zones while the drawdowns were in progress. Liquid water (e.g., groundwater seeps, runoff, inflow, etc.) was one factor that seemed to allow for zebra mussel survival in otherwise dewatered areas. This observation is consistent with laboratory experiments showing that zebra mussel survival to aerial exposure is positively related to relative humidity (Paukstis et al., 1999; Ricciardi et al. 1995). Snow cover may be another important mitigating variable. Early and continuing snow cover is known to reduce the efficacy of winter lake drawdowns for “weed control” by reducing freezing and drying of the target aquatic macrophytes (Holdren et al., 2001). Based on the Edinboro Lake work, it appears that snow cover may reduce the efficacy of winter lake drawdowns for zebra mussel control in a similar manner. Despite unseasonably warm temperatures, zebra mussel mortality was significantly greater in Edinboro Lake during the 2001 than 2000 drawdown. We hypothesize that the relatively lower efficacy of the 2000 drawdown is related to the 45+ cm thick blanket of snow covering Edinboro Lake during the 2000 drawdown period. Accordingly, potential snowpack should factor prominently into decisions regarding fall/winter drawdown timing and duration in snow-belt areas. Projected air temperatures are another important variable to consider. Paukstis et al. (1996) demonstrated that zebra mussels acclimated to a temperature of 2.0 °C in the laboratory have the ability to supercool (prevent tissue freezing) to a temperature of -3.0 °C. These data suggest that prolonged exposure may be necessary when ambient air temperatures are warmer than -3.0 °C. In general, warmer temperatures will require longer aerial exposure times to achieve comparable levels of control during a fall-winter drawdown (c.f., Payne 1992). Given that it is highly unlikely that the entire zebra mussel population will be aerially exposed during a drawdown and that some zebra mussel survival should be expected even in the dewatered zone of the lake, complete eradication of the zebra mussel population via fall/winter lake drawdown is not a realistic goal. Periodic drawdowns will be necessary for continuing zebra mussel control.

Summer lake drawdowns for zebra mussel control have also been proposed (e.g., Paukstis 1999; Ricciardi et al., 1995; Tucker et al., 1997). In our opinion, however, fall/winter lake drawdowns offer several compelling advantages. First and foremost, zebra mussel veligers are present in the water column throughout most of the summer months. Therefore, lake drawdowns during this period would serve to increase the efflux of veligers through the lake's outlet stream with the possible unintended consequence of increased downstream colonization. Moreover, suspended veligers would presumably not be affected by the drawdown, resulting in rapid recolonization of the dewatered zone when lake levels are ultimately raised (Tucker et al., 1997). Secondly, summer drawdowns have a greater potential to disrupt summer recreational uses of the lake (i.e., boating and fishing) and, in the case of hydropower impoundments, diminish water supplies at a time when power demands are at a premium. Thirdly, freezing temperatures will allow for better kill of zebra mussels in otherwise protected microhabitats (e.g., in pockets with high relative humidity beneath dewatered aquatic vegetation and rocks).

While we feel that fall and winter lake drawdowns can be an effective zebra mussel control strategy in some lakes, we caution resource managers against the indiscriminate use of this technique. Even on lakes with suitable water level control structures, mitigation drawdowns are of little value where the majority of the zebra mussel population lies in water deeper than the proposed (or attainable) drawdown depth. Pre-drawdown mussel distribution surveys are critical, therefore, in determining the likely success of a proposed drawdown for zebra mussel control. Where pre-drawdown surveys indicate the potential for high levels of zebra mussel control, resource managers should carefully weigh the costs and benefits associated with the proposed drawdown. For example, desirable side effects of winter lake drawdowns for zebra mussel control include the opportunity to repair previous shoreline erosion damage, conduct maintenance on docks, retaining walls, and water control structures, and control nuisance littoral aquatic macrophytes. Conversely, winter lake drawdowns can have serious unintended consequences. Ice safety concerns are paramount in northern US lakes since winter drawdowns can render ice unstable for skaters and ice fisherman. Effective public outreach, including posting lake access points with hazard warning signs, is essential prior to conducting a winter drawdown.

Impact of the drawdown to non-target species, while not formally investigated during the present studies, is also of primary concern. For example, Hall and Cuthbert (2000) caution that stress and injury related to fall drawdowns may increase turtle morbidity and mortality. Unionid mussel losses have also been shown to result from both winter (Howells et al., 2000) and summer (Tucker et al., 1997) lake drawdowns, although unionids appear to be more resistant to short-term (24h) aerial exposure during summer conditions than do zebra mussels (Tucker et al., 1997). In the case of impact to non-target species, however, it is important to consider both potential impacts from the proposed drawdown as well as impacts related to the "do nothing" alternative. For example, zebra mussels regularly colonize (foul) native unionid mussels, with densities of up to 14,000 zebra mussels per unionid reported where zebra mussel population densities are high (Schloesser and Nalepa, 1994). Fouling by zebra mussels can kill the host unionid directly (e.g., by preventing the unionid from opening its valves to feed and respire) or indirectly (e.g., by competition for food). Zebra mussels have caused the extirpation of unionids from many waterbodies in North America and can cause serious impacts to unionid populations even at low unionid colonization densities (see Strayer 1999 for a review of this topic).

Other potential side effects of winter drawdowns include loss or reduction of desirable plant species, facilitation of invasion by drawdown-resistant undesirable plant species, more frequent algal blooms after refill (in some cases), impacts to connected wetlands, reduced attractiveness to waterfowl, changes in fish and invertebrate habitat (including potential fish winterkill), and reduction in water supply to water intakes and well users (e.g., Holdren et al., 2001). Depth, duration, frequency, and timing are critical planning elements of any lake drawdown, including one proposed for zebra mussel control.

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